EXOPLANET EXPLORATION PROGRAM

PATH FORWARD: FUTURE NASA MISSIONS, TECHNOLOGY DEVELOPMENT PLANNING

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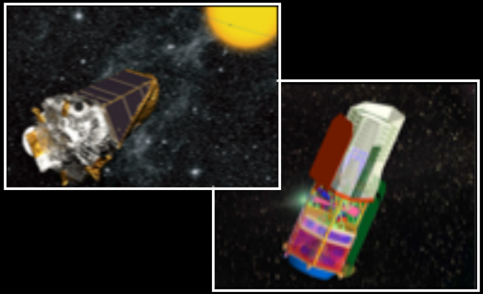
February 27, 2014

URSCL#14-0035, URSCL#13-4970, URSCL#13-5453


Exoplanet
Missions
JWST
AFTA
TESS
Kepler
New Worlds
Telescope
Spitzer
Hubble
Ground-based
Observatories
Astronomy and Astrophysics
in the New Millennium
2001
Decadal
Survey
New Worlds,
New Horizons
in Astronomy and Astrophysics
2010
Decadal
Survey
URSCL#13-4970

The Search for Life in the Universe Requires η_{Earth}



<u>Complete the census</u>

Kepler (warm)

WFIRST μ-lensing (cool)

<u>Find nearby transiting planets</u>

TESS

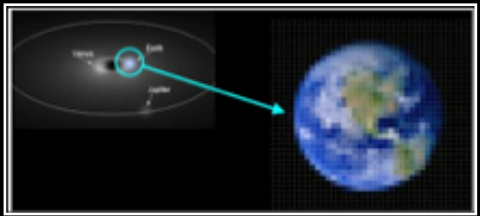
<u>Characterize super-earth/mini-Neptunes</u>

JWST

<u>Imaging and Spectroscopy of planets</u>

WFIRST-AFTA coronagraph (Jupiters, Neptunes, Super-Earths)

New Worlds Mission (Earth 2.0)



N. Batahla

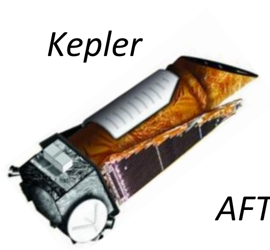
The Exoplanet Exploration Program: Exploring New Worlds

ExEP
ExoPlanet Exploration Program

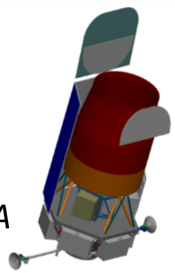
***Exploring** How the Universe Works*
***Discovering** and Characterizing Exoplanets*
***Searching** for Signs of Life in the Galaxy*

Space Missions and Mission Studies

Kepler

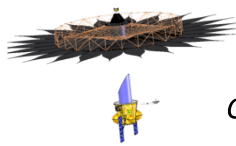


AFTA



Probe-Scale:

External Occulter (Starshade)



Coronagraph

Public Engagement

Supporting Research & Technology

Key Sustaining Research

Keck Single Aperture Imaging and RV

Large Binocular Telescope Interferometer

Technology Development

High Contrast Imaging

Deployable Star Shades

Archives, Tools & Professional Education

NASA Exoplanet Science Institute

Exoplanet Exploration Program Organization Chart

ExoPlanet Exploration Program

Astrophysics Division, NASA HQ
Director – Dr. P. Hertz
Deputy Director/Program Director – A. Razzaghi

Exoplanet Prog. Exec. – Dr. A. Carro
Exoplanet Prog. Sci. – Dr. D. Hudgins

AFTA Program Executive – L. LaPiana
AFTA Program Scientist – Dr. D. Benford
Kepler Program Executive – Dr. A. Carro
Kepler Program Scientist – Dr. D. Hudgins
NExScI, LBTI Prog. Exec. – Dr. M. Perez
NExScI, LBTI Prog. Sci. – Dr. H. Hasan

Astronomy Physics & Space Technology Directorate, JPL
Director for – D. Gallagher
Deputy Director for – Dr. D. Coulter

730
Exoplanet Exploration Program Office
Program Manager – Dr. G. Blackwood
Deputy Program Manager - Vacant
Program Chief Scientist – Dr. W. Traub (3200)
Program Technologist – Dr. P. Lawson (3800)

ExoPlanet TAC[1]
Dr. A. Boss
Carnegie Institute

7301
Program Science Office
Scientist - Dr. S. Unwin (312)
AFTA - Dr. D. Stern (326)
AFTA – Dr. G. Bryden (326)

7303
Program Engineering Office
Manager - Vacant

7304
Program Business Office
Manager – Vacant
Resource Analyst – L. Scott (252)
Export Tech Lia. – Dr. A. Abramovici (383)
Administrator – O. Pananyan (720)
Project Schedule Analyst – K. McClane (252)
Staff Assistant – K. Miller (730)
Staff Assistant - M. Rubio (730)

Exoplanet Probe Study Office
K. Warfield (312)

Exoplanet Probe STDT - Starshade[1]
Dr. S. Seager, MIT

Exoplanet Probe STDT - Coronagraph[1]
Dr. K. Stapelfeldt, GSFC

Mission Managers / Scientists
Kepler Mission Mgr – I. Heinrichsen (734)
Kepler Mission Sci – Dr. N. Gautier (326)
WFIRST Mission Mgr – I. Heinrichsen (730)
WFIRST Mission Sci – Dr. S. Unwin (312)

790
NASA Exoplanet Science Institute (Caltech)
Exec. Director –
Dr. C. Beichman (790)
Deputy Director – Dr. R. Akeson
Manager – Dr. D. Imel

Ground Observatories & Suborbital Activity
Manager – Dr. D. Imel
Keck Project Scientist –
Dr. R. Akeson

Kepler (ARC)
Project Manager (Phase E) – R. Hunter
Project Scientist (Phase E) – Dr. S. Howell
Science PI – W. Borucki

7330
Program Technology (JPL)
Manager – Dr. N. Siegler (383)

7302
Program Education & Public Outreach (JPL)
EPO Manager – M. Greene (183)
Web Manager – R. Jackson
Web Editor – J. Rodriguez
EPO Coordinator – A. Biferno

7320
LBTI (Univ. of Arizona)
Manager – B. Parvin (730)
Principal Investigator – Dr. P. Hinz, U of A
Project Scientist – Dr. R. Milan-Gabet

AFTA Study Office (GSFC)
Study Manager – K. Grady
Study Scientist – Dr. N. Gehrels

AFTA SDT[1]
Prof D. Spergel
Princeton University
Dr. N. Gehrels
GSFC

AFTA Study Office (JPL)
Telescope – B. Parvin (730)
Coronagraph – Dr. F. Zhao (383)
Technology – Dr. N. Siegler (383)

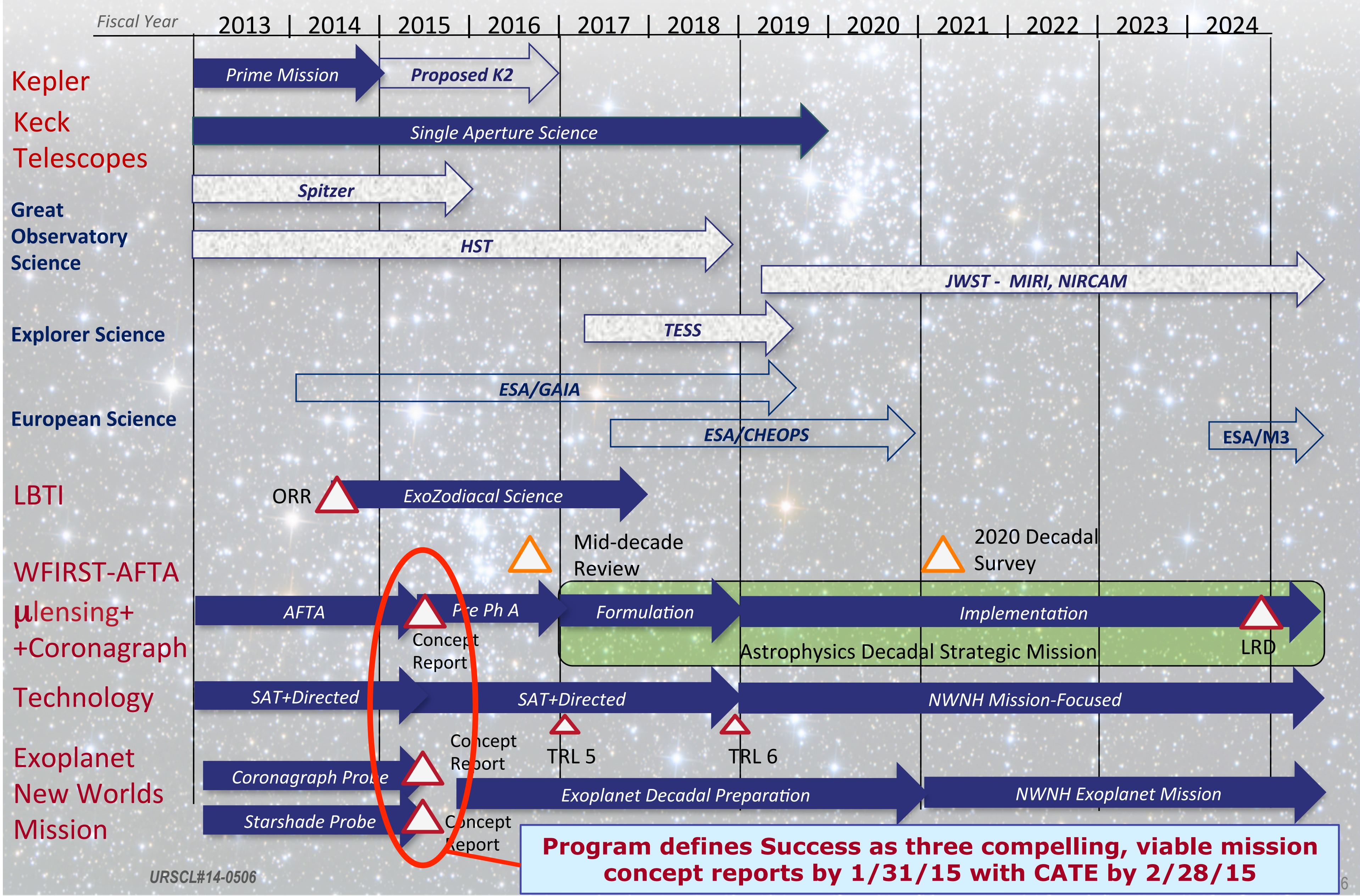
AFTA TAC
Dr. A. Boss
Carnegie Institute

[1]Reports to HQs APD

Exoplanet Exploration: A Decade Horizon

NASA and related ESA efforts

ExoPlanet Exploration Program



Astrophysics Budget Strategy

- In order to be prepared for a new mission, a near term program of science definition teams, mission concept studies and technology development is being undertaken with the goal of informing a mid-decade decision on whether to begin formulation.
- Moderate missions (“probes”) are being studied, in addition to a large mission (WFIRST), to be prepared for a mid-decade decision.
- Mission concepts studied derive from the science objectives of the prioritized missions and recommendations in the 2010 Decadal Survey.
  - AFTA (WFIRST using existing 2.4 m telescopes)
  - WFIRST (2 design reference missions already studied, including WFIRST-probe)
  - X-ray Astrophysics Probe (moderate mission addressing IXO science)
  - Exoplanet Probes (moderate missions using internal or external occulters)

Preparing the next strategic mission

FY2012	FY2013	FY2014	FY2015	FY2016	FY2017

Spring 2013: Begin AFTA studies following Administrator's decision

Identified SDT studies:
Versions of WFIRST (2012)
Exoplanet probe(s) (2013)
X-ray probe (2013)

Spring 2014: Interim SDT reports to NASA and CAA

Winter 2015: Final SDT reports to NASA and CAA; CATE on each

Spring 2015: NRC study of all SDT reports resulting in a NRC letter report

Initiate NRC Mid-Decade Review

Start Pre-formulation for new strategic mission
- Directed/Focused technology development

Complete NRC Mid-Decade Review

Revise plans as necessary in response to Mid-Decade Review report

Formulation new start for strategic mission

Astrophysics Implementation Plan (CY2012)	Astrophysics Roadmap (CY2013)

ESA's L2/L3 process

Directed Technology investments for prime candidate

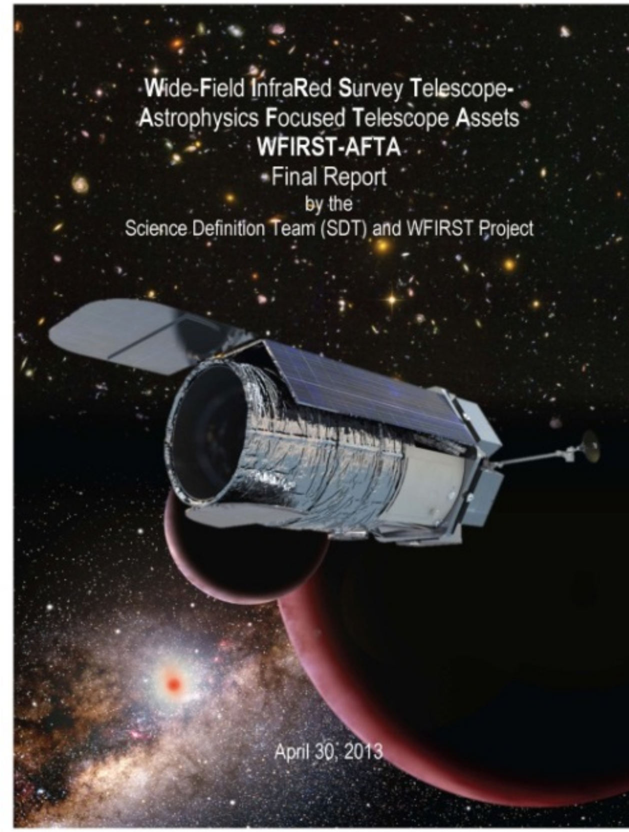
Technology Investments through SAT for prioritization

Technology Investments through SAT for 2020 Decadal Survey

Continuing advice from the Committee on Astronomy and Astrophysics on decadal survey implementation

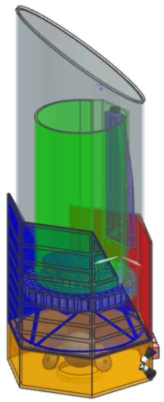
AFTA Coronagraph: Architecture Selection

- AFTA Coronagraph Working Group completed intensive workshops during July-Dec 2013
- 12/23: Coronagraph architectures selected for continued study:
  - Primary: Occulting Mask Coronagraph (OMC), single optical design incorporating both Hybrid Lyot (HL) and Shaped Pupil (SP) masks
  - Backup: Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAA-CMC)
- Observatory jitter analysis phased forward. Latest jitter estimates (lower) plus re-optimized HL permits detection of ~18 existing RV planets.
- Next steps on coronagraph:
  - Prepare milestones (1/31) and final tech plan (2/28)
  - Implement competed technology per plan (more than just masks)
- H4RG-10 detectors: 3 of 4 under test GSFC

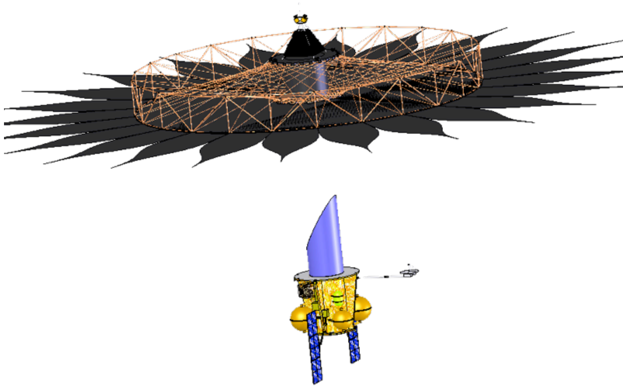


Probe-Scale Missions

- Trades well underway, preparation of interim report
- Initial Aerospace review of baseline concepts
- Science evaluations suggest compelling science
- Exo-C (Coronagraph)
  - Primary mirror 1.5m
  - Kepler-class telescope and spacecraft
  - Thermal and pointing architectures settled
  - Earth-trailing orbit
- Exo-S (Starshade)
  - Earth-leading orbit
  - Starshade stationary, telescope moves
  - Primary mirror 1.1m
- Technology gap lists and plans being prepared, prioritized



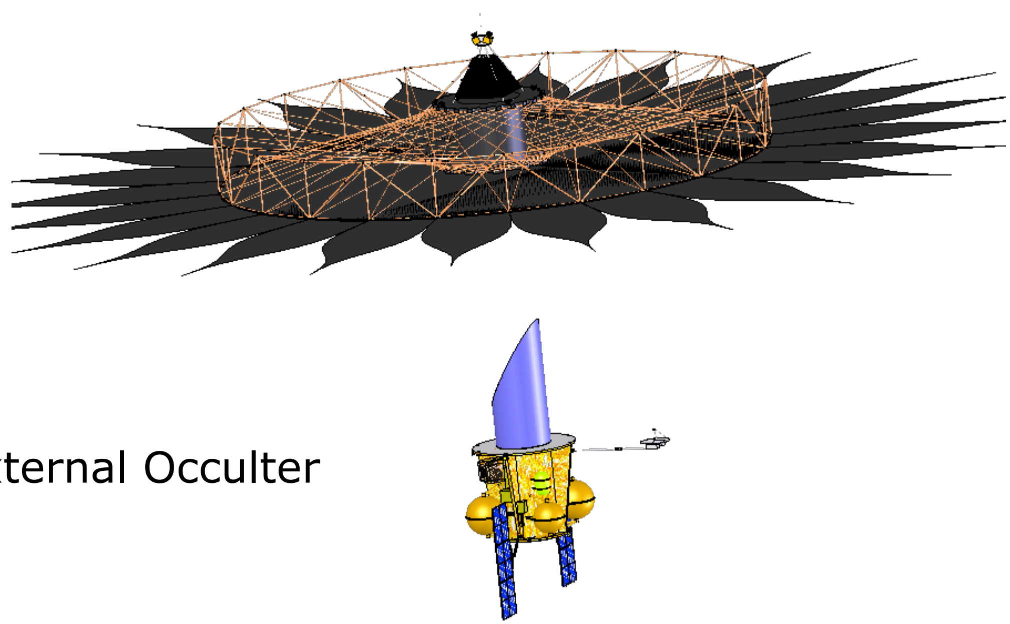
EXO-C



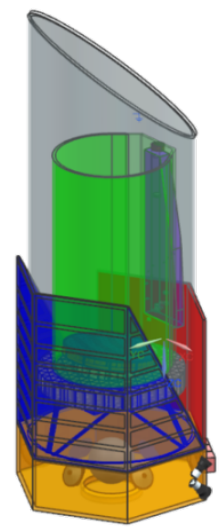
EXO-S

Probe-Scale Missions

- Two probe-scale ($1B) mission concepts under development by Science and Technology Definition Teams (STDTs)
  - Exo-S (Starshade, or External Occulter) Sara Seager, MIT, chair
  - Exo-C (Coronagraph) Karl Stapelfeldt, GSFC, chair
- Purposes: Alternatives for FY17 new mission start, motivate technology investments, potential candidates for 2020 Decadal



External Occulter



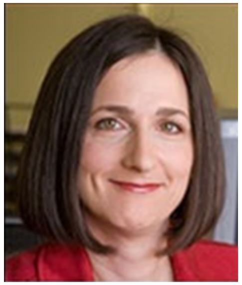
Coronagraph

STDT Membership

Last	First	Organization
* Stapelfeldt	Karl	NASA Goddard Space Flight Center
Belikov	Rus	NASA Ames Research Center
Bryden	Geoff	Jet Propulsion Laboratory
Cahoy	Kerri	Massachusetts Inst. of Technology
Chakrabarti	Supriya	Univ. of Massachusetts, Lowell
Marley	Mark	NASA Ames Research Center
McElwain	Michael	NASA Goddard Space Flight Center
Meadows	Vikki	Univ. of Washington
Serabyn	Gene	Jet Propulsion Laboratory
Trauger	John	Jet Propulsion Laboratory
* Chair		

Karl Stapelfeldt
GSFC
Chairperson

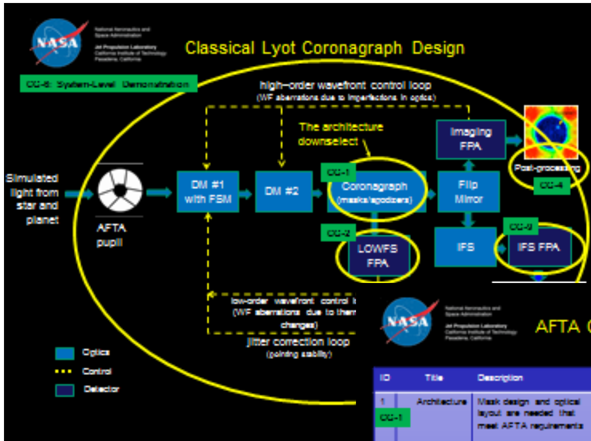
Last	First	Organization
* Seager	Sara	Massachusetts Inst. of Technology
Cash	Webster	Univ. of Colorado
Domagal-Goldman	Shawn	NASA Goddard Space Flight Center
Kasdin	N. Jeremy	Princeton Univ.
Kuchner	Marc	NASA Goddard Space Flight Center
Roberge	Aki	NASA Goddard Space Flight Center
Shaklan	Stuart	Jet Propulsion Laboratory
Sparks	William	Space Telescope Science Institute
Thomson	Mark	Jet Propulsion Laboratory
Turnbull	Margaret	Global Science Institute
* Chair		

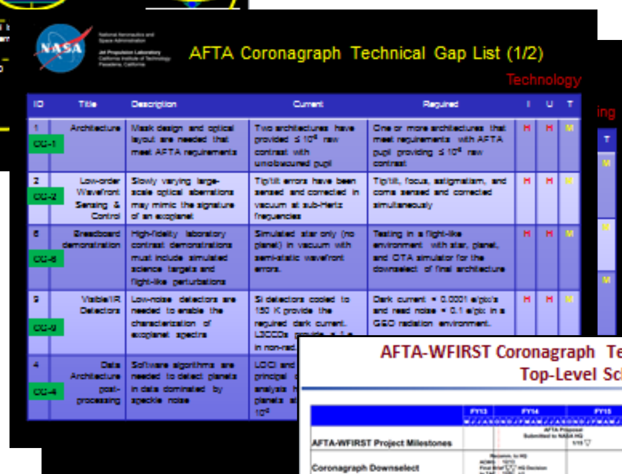


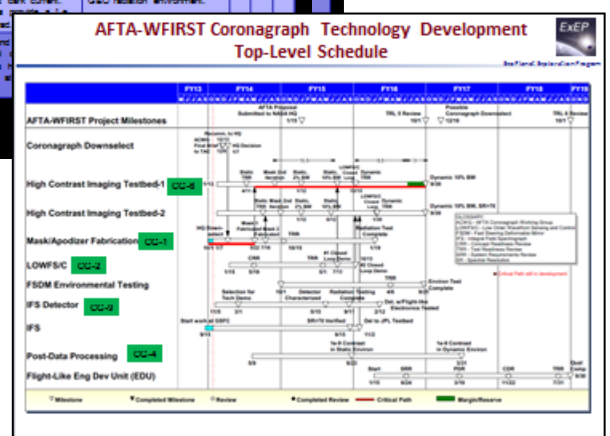
Sara Seager
MIT
Chairperson

Prioritization: the Technology Gap List

ExoPlanet Exploration Program







- Technology gaps identified and described, gaps technically quantified
- Prioritized for relative Importance, Urgency, and Trend
- Plans created to retire the top priorities in time
- AFTA TGL described to SMD/STMD
- Next steps: do same for Starshade, Probe Coronagraph

Technology Gap Lists: Key Gaps

STARSHADE

ID	Title	Description
S-1	Control of Scattered Sunlight	Sunlight scattered from starshade edges and surfaces risks being the dominant source of measurement noise.
S-2	Starshade Deployment	Demonstrate that an starshade can be deployed to within the budgeted tolerances.
S-3	Validation of starshade optical models	Experimentally validate the equations that predict the contrasts achievable with a starshade
S-4	Thermal & Mechanical Dynamic Stability	The deployed tolerances must be maintained under typical observing conditions, including starshade rotation.
S-5	Formation Flying GN&C	Demonstrate that the GN&C system for an occulter will enable the required slew from star to star and positional stability for science observations.
S-6	Flight Performance System Modeling	Demonstrate using experimental data and validated thermo-mechanical and optical models that the full-scale flight occulter will achieve its baseline performance.

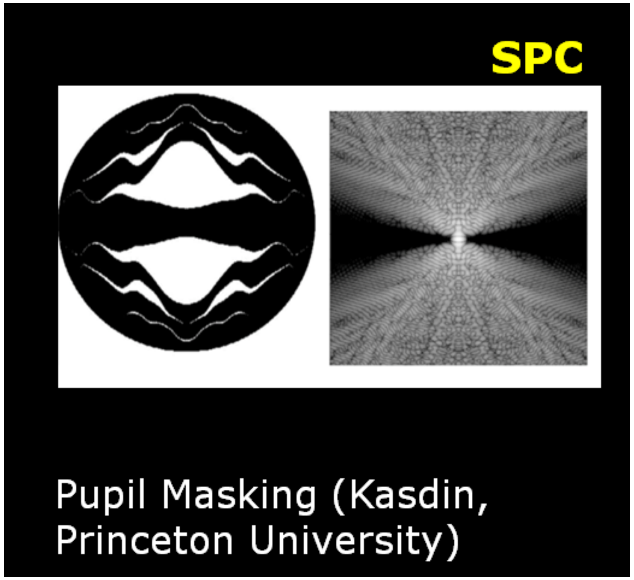
- Gap lists are work-in-progress by Probe STDTs, per their charter
- These program summaries will form basis of next Technology Plan Appendix, referenced by TDEM-13 call
- Intended Result: quality proposals that address the breadth of top priorities

See Lawson, AAS 2014, and upcoming Tech Plan Appendix

CORONAGRAPH

ID	Title	Description
C-1	Starlight suppression optics	Masks, apodizers, or beam-shaping optics to provide improved planet detection capability.
C-2	Low-order Wavefront Sensing & Control	Slowly varying large-scale optical aberrations may mimic the signature of an exoplanet.
C-3	Exoplanet detection under flight-like conditions	High-fidelity laboratory contrast demonstrations that include simulated science targets and flight-like perturbations.
C-4	Deformable mirrors	Maturation of deformable mirror technology to flight readiness.
C-5	Pointing Control System Design	Validation of pointing control design for instrument fine steering mirror and spacecraft body pointing.
C-6	Flight Performance System Modeling	Demonstrate using experimental data and validated thermo-mechanical and optical models that the full-scale flight coronagraph will achieve its baseline performance.

Coronagraph Technologies



- ExEP Technology Plan Appendix:
- http://exep.jpl.nasa.gov/technology/

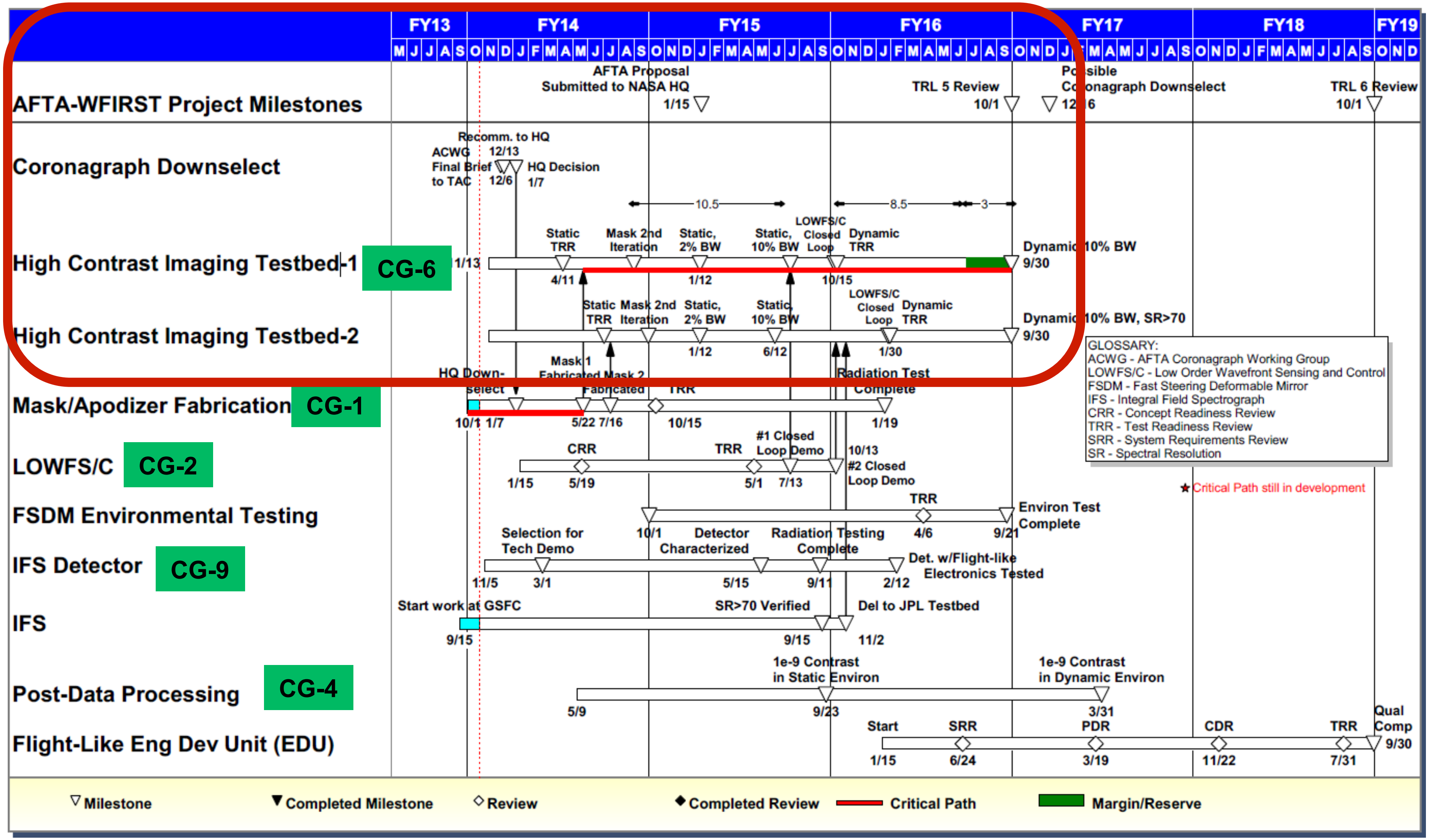
Table A.3 Coronagraph Technology Gaps Listed in Priority Order.

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide improved planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks with a larger discovery space and IWA $\leq 3\lambda$/D with contrasts $\leq 1\times10^{-9}$ for NWNH.
C-2*	Low-order Wavefront Sensing & Control	Slowly varying large-scale optical aberrations may mimic the signature of an exoplanet.	Tip/tilt errors have been sensed and corrected in vacuum with a stability of 0.001 λ/D at sub-Hertz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to maintain raw contrasts of $\leq 1\times10^{-9}$ for NWNH.
C-3*	Coronagraph System-level Performance Demonstration	High-fidelity laboratory contrast demonstrations that include simulated science targets and flight-like perturbations.	Star-only (no planet) contrast demonstrations in vacuum with an unobscured pupil and semi-static wavefront errors.	Testing in a flight-like dynamic environment with star, planet, and optical telescope assembly simulator with the telescope-specific pupil obscuration.
C-4*	Ultra-low Noise Detector	Low-noise detectors for exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e-/pixel has been demonstrated with EMCCDs in a 1k × 1k format.	Read noise < 0.1e-/pixel in a ≥ 2k × 2k format in a flight-like radiation environment.
C-5	Deformable mirrors	Maturation of deformable mirror technology toward flight readiness.	Xinetics DMs and MEMS DMs have undergone partial environmental testing (see text).	Development of flight-like electronics. Full environmental system testing with post-test performance validation.
C-6*	Post-processing of Data	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Planets with contrasts between 10^{-5} and 10^{-6} have been detected in the near infrared.	Techniques must enable exoplanet characterization of of exoplanets with contrasts $\leq 10^{-10}$ for NWNH.

*Topic being addressed by directed-technology development for the AFTA coronagraph. To avoid redundancy, coronagraph technologies that will be substantially advanced under the AFTA-WIFRST technology development are not eligible for under the auspices of the SAT Program.

AFTA-WFIRST Coronagraph Technology Development Top-Level Schedule

ExoPlanet Exploration Program

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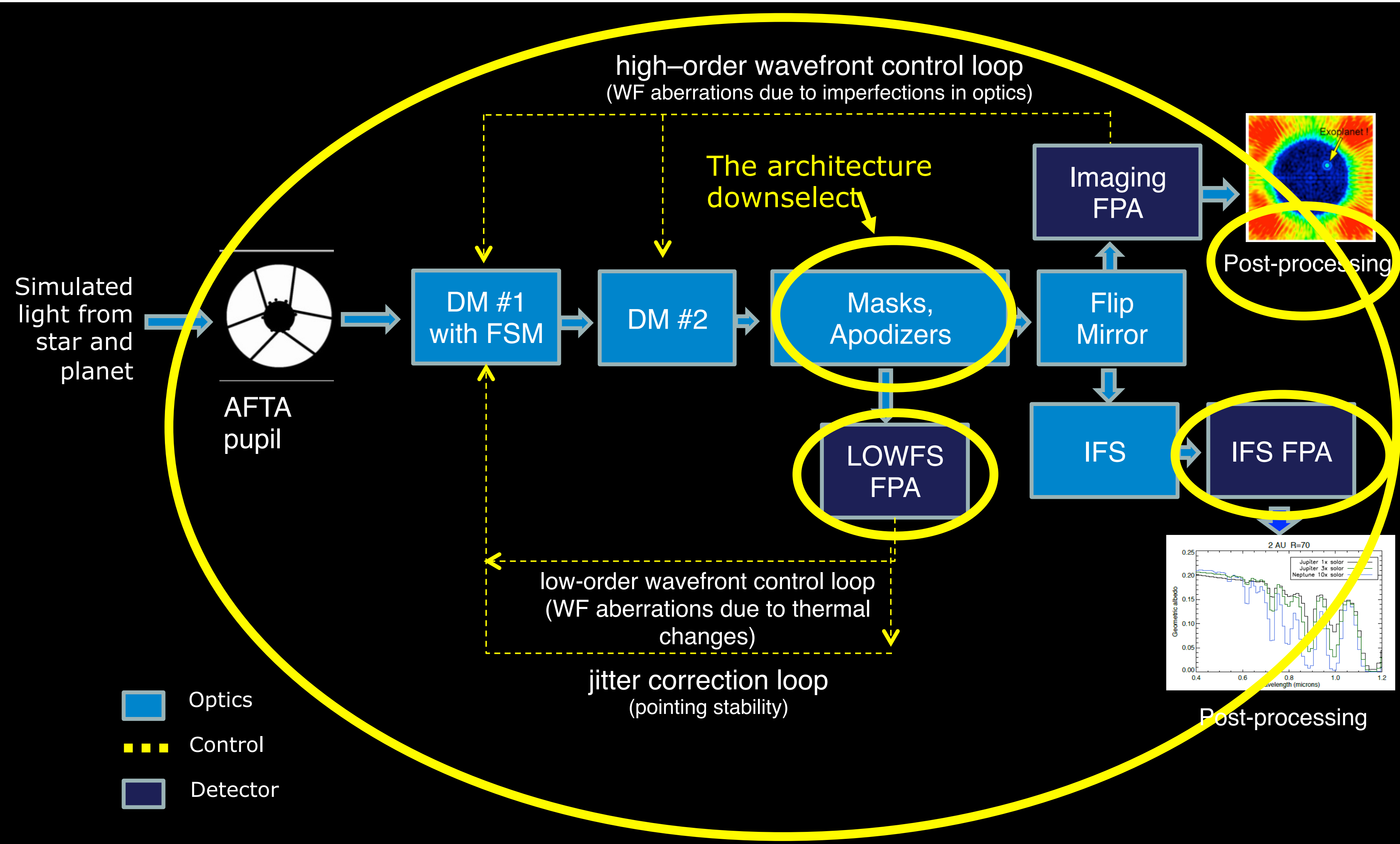
BACKUP

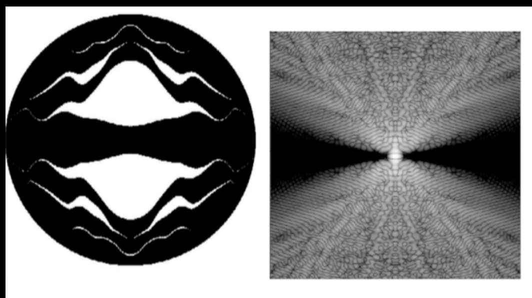
Coronagraph Instrument: Several Technologies

Example: Classical Lyot Coronagraph Design



Coronagraph Mask Architectures

SPC



Pupil Masking (Kasdin, Princeton University)

HLC

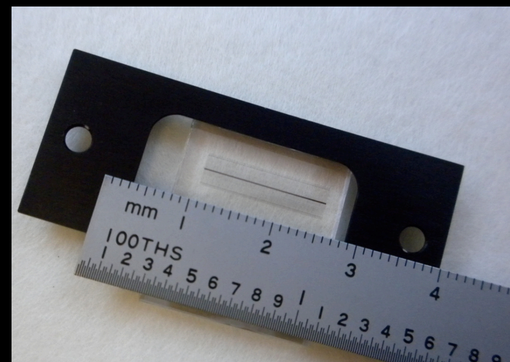
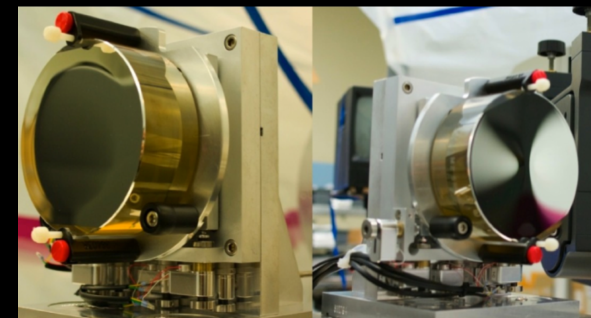


Image Plane Amplitude & Phase Mask (Trauger, JPL)

PIAACMC



Pupil Mapping (Guyon, Univ. Arizona)

VVC

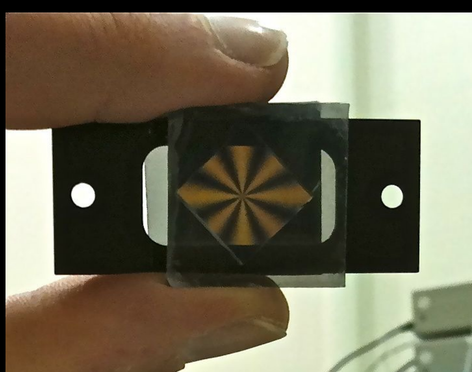
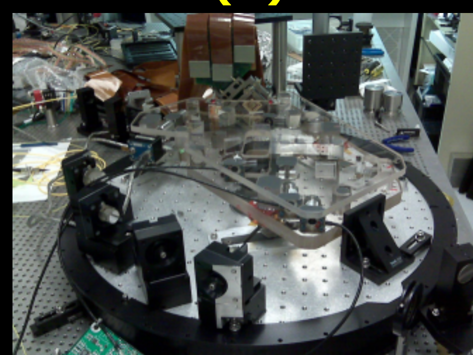


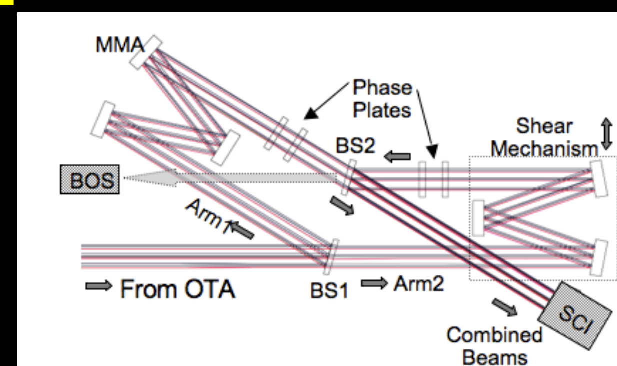
Image Plane Phase Mask (Serabyn, JPL)

VNC(2) - DAVINCI



Visible Nulller - DAVINCI (Shao, JPL)

VNC-PO



Visible Nuller – Phase Occulting (Clampin, NASA GSFC)